APPENDIX V

DETAILS OF TRANSPORTATION ACCIDENTS

I-6

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APPENDIX V

DETAILS OF TRANSPORTATION ACCIDENTS

V.1 Types of Accidents and Incidents

Four different types of events can interfere with routine transportation of spent nuclear fuel:

- A minor traffic accident ("fender-bender," flat tire), resulting in minor damage to the vehicle. These are usually called "incidents."[1]
- An accident which damages the vehicle and or trailer and cask severely enough that the vehicle cannot move from the scene of the accident under its own power, but the accident does not result in any release of radioactive material. This accident type includes train derailments..
- Accidents in which there loss of lead gamma shielding but no release of radioactive material.
- Accidents in which there is a release of radioactive material.

In this analysis the first two types are considered together, since neither type involves a release of radioactive material. The NAC-STC is the only cask studies that uses a lead gamma shield, and is therefore the only cask that could be involved in an accident causing a loss of lead gamma shielding. The shielding could thin or develop a gap in an accident. The HISTAR-100 rail cask is a monolithic steel cask and is loaded with canistered fuel, so that even in an accident there would be no release of radioactive material. Chapter 3 and Appendix III discuss the accident behavior of the GA-4 truck cask, which uses a depleted uranium (DU) gamma shield, and conclude that the GA-4 will not release radioactive material in any achievable accident. Accidents that involve the HISTAR-100 and the GA-4 are limited to the first two types described above, as discussed in Chapter 5. The NAC-STC could either lose lead shielding or release radioactive material in an accident, and is the only cask of the three whose behavior is discussed in this appendix.

Comment [JRC1]: Agree with this approach.

Deleted: "no-release"

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V.2 Accident probabilities

V.2.1 Historic accident frequencies

The probability that a traffic accident happens is based on historic accident frequencies. These have been developed and the statistics validated by the Department of Transportation (DOT). Table V-1 shows truck and railcar accidents from 1991 through 1997 (DOT, 2008). Average accident frequencies for this period are:

[1] In Department of Transportation parlance, an "accident" is an event that results in a death, an injury, or enough damage to the vehicle that it cannot move under its own power. All other events that result in non-routine transportation are called "incidents." This document uses the term "accident" for both accidents and incidents.

- 1.87×10^{-6}/km for large trucks on interstates and primary highways.
- 1.08×10^{-7}/railcar km for freight rail

Accident frequencies decreased 33.5 percent for trucks and 53.8 percent for railcars between 1991 and 2007. The average is used in this document because there are annual fluctuations. The accident frequency trends are shown in Figure 5.2 in Chapter 5.

Table V-1. Truck and railcar accidents per km, 1991 through 2007.

YEAR	TRUCK ACCIDENTS/KM	ACCIDENTS PER RAILCAR/KM
1991	2.39×10^{-6}	2.08×10^{-7}
1992	1.99×10^{-6}	1.91×10^{-7}
1993	2.19×10^{-6}	1.68×10^{-7}
1994	2.19×10^{-6}	1.64×10^{-7}
1995	2.39×10^{-6}	1.53×10^{-7}
1996	1.90×10^{-6}	1.39×10^{-7}
1997	1.89×10^{-6}	1.32×10^{-7}
1998	2.04×10^{-6}	1.19×10^{-7}
1999	1.84×10^{-6}	1.12×10^{-7}
2000	2.08×10^{-6}	1.12×10^{-7}
2001	1.99×10^{-6}	1.18×10^{-7}
2002	1.83×10^{-6}	1.12×10^{-7}
2003	1.85×10^{-6}	1.02×10^{-7}
2004	1.90×10^{-6}	1.00×10^{-7}
2005	1.73×10^{-6}	1.06×10^{-7}
2006	1.83×10^{-6}	1.04×10^{-7}
2007	1.59×10^{-6}	9.60×10^{-8}

V.2.2 Development of Conditional Accident Probabilities

Each specific accident scenario is described by a conditional probability ("conditional" on an accident happening). Conditional probabilities are derived from event trees, as described below.

V.2.2.1 Conditional probabilities of truck accidents

A transportation accident scenario can be disaggregated into a series of events. The conditional probability of a particular event in the scenario is best illustrated with an event tree: a diagram that includes all possible accident scenarios. Each branch of the tree is the series of events that comprise a particular accident scenario. The conditional probability is the product of the probabilities along a particular branch.

Figures V-1 is an event trees for truck accidents (Mills, et al, 2006). Calculation of the conditional probability of a truck in a collision with another vehicle on a bridge, then falling from the bridge onto a rocky embankment, is illustrative.

$$P_{conditional} = P_{collision} * P_{bridge\ accident} * P_{fall\ off\ bridge} * P_{rocky\ soil}$$

$$P_{conditional} = (0.054)*(0.064)*(0.02)*(0.046) = 3.18 \times 10^{-6}$$

The conditional probabilities are listed in the right-hand column of Figure V-1.

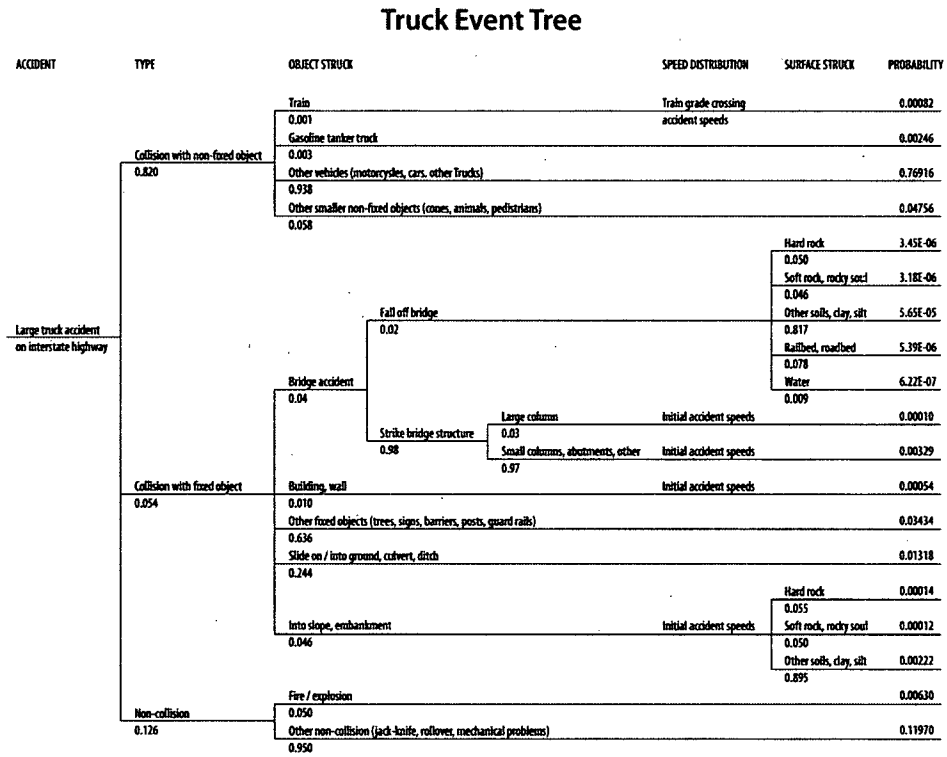

Figure V-1 Event tree for highway accidents (from Mills, et al, 2006)

The construction of the event tree of Figure V-1 is described in detail in Mills, et al (2006). Details of collision accidents are discussed in Appendix III and of fire accidents, in Appendix IV.

V.2.2.2 Conditional probabilities of rail accidents

Figure V-2 is an event tree for rail.

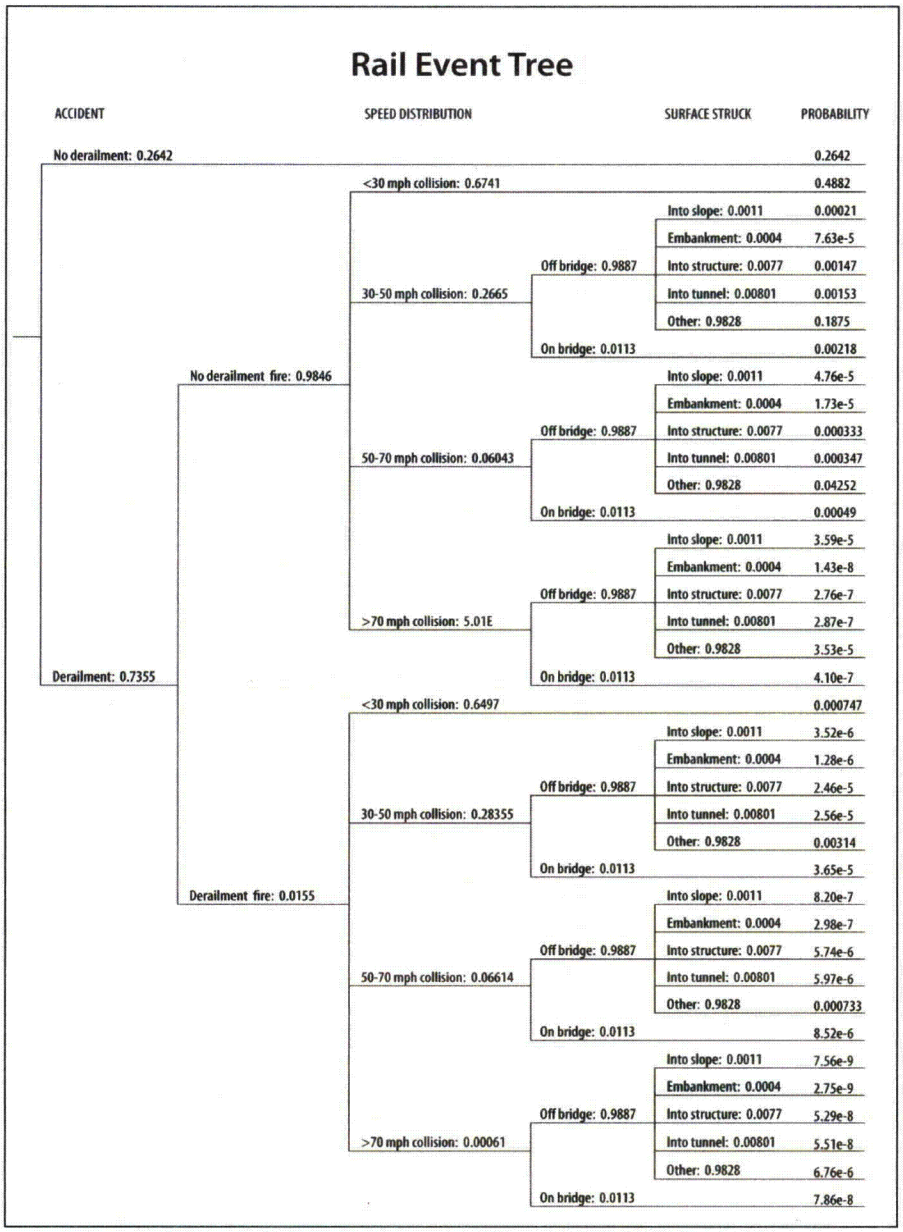

Figure V-2 . Rail accident event tree (after Volpe, 2006)

V.3. Accident Risks and Consequences

V.3.1 Loss of lead gamma shielding

The cask studied that uses lead as gamma shield is the NAC-STC, a rail cask, so loss would occur only in rail accidents . The NAC-STC gamma shield is a lead cylinder about 0.127 m. thick. The lead shell can slump in a sufficiently severe impact, leaving a gap in the lead shield which results in increased external gamma radiation . RADTRAN models a gap in the shield from an impact and translates this to an increase in the dose from the virtual radiation source (O'Donnell, et al., 2005; Dennis, et al., 2009) that is the basis for the incident-free transportation model (Figure II-1, Appendix II). Figure V-3 is a diagram of the loss-of-shielding model, which recognizes the two-dimensional symmetry of the lead-shielded cask.

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Comment [JRC3]: Should show the "side 1" and "side 2" and different impact orientations found in following tables.

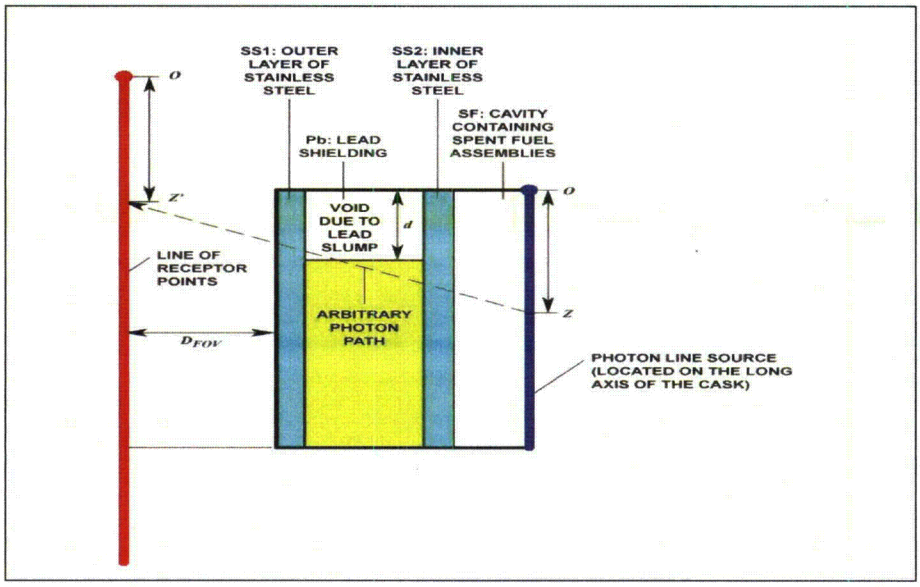

Figure V-3. The RADTRAN Loss-of Shielding 2-D Model (O'Donnell, et al, 2005)

V.3.1.1 Loss of lead shielding from impact

Appendix III (. Section 3.2.2) described the various amounts of lead slump resulting from impact speed and aspect. Table V-2 shows the conditional probabilities of each combination of impact speed and orientation. The conditional probabilities are those of a fall from the bridge into a tunnel, a collision on the bridge, and a fall from a bridge onto hard rock (Mills et al, 2006, Table 9). Table V-3 shows the slump as fractions of the longest dimension of the lead shield and combines the conditional probabilities in Table V-2 for each applicable accident scenario in the rail event tree (Figure V-2). Only the lead-shielded NAC-STC rail cask might lose shielding in an accident.

Comment [JRC4]: Where did this come from – does not appear to belong to this para?

As Tables V-2 and V-3 show, the lead slump on opposite sides of the cask is different following a corner or side impact. This is particularly noticeable with the side impact. A radiation dose to any exposed person or population would therefore differ depending on the side of the cask to which the receptor was exposed. Table V-4 shows doses to the maximally exposed individual (MEI) at various distances from the cask. Table V-6 shows the population that could be exposed for each of the sixteen routes modeled.

Table V-2. Parameters of lead shield slumping from impact.

Orientation	Impact Speed kph	Event Tree Impact Speed mph	Location (Side 1 or Side 2)	Maximum Slump (mm)	Conditional Probability from Rail Event Tree and 5%>90 mph	Conditional Probability including Orientation[a]
End (Probability = 0.1)	193	>113	1	355.40	1.34E-07	1.34E-08
			2	355.48		
	145	>113	1	83.20	2.54E-06	2.54E-07
			2	82.68		
	97	80 to 113	1	18.28	8.27E-04	8.27E-05
			2	18.21		
	48	48 to 80	1	6.43	2.35E-03	2.35E-04
			2	6.42		
Corner (Probability= 0.6)	193	>113	1	310.48	1.34E-07	8.03E-08
			2	254.56		
	145	>113	1	114.52	2.54E-06	1.53E-06
			2	80.35		
	97	80 to 113	1	25.11	8.27E-04	4.96E-04
			2	20.55		
	48	48 to 80	1	1.28	2.35E-03	1.41E-03
			2	1.65		
Side (Probability= 0.3)	193	>113	1	0.53	1.34E-07	4.01E-08
			2	15.47		
	145	>113	1	0.43	2.54E-06	7.63E-07
			2	20.88		
	97	80 to 113	1	0.00	8.27E-04	2.48E-04
			2	1.37		
	48	48 to 80	1	0.06	2.35E-03	7.05E-04
			2	0.09		

Comment [JRC5]: What is the distinction?

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Comment [JRC6]: Footnote not explained.

Table V-3. Fractions of lead shielding lost and conditional probabilities

Side Affected	Fraction of Shield. Lost	P_{cond}
1 or 2	0.0725	$8.03X10^{-8}$
1	0.0634	$2.41X10^{-7}$
2	0.0520	$2.41X10^{-7}$
1	0.0234	$4.58X10^{-6}$
1 or 2	0.0170	$7.63X10^{-7}$
2	0.0164	$4.58X10^{-6}$
1	0.00512	0.00149
2	0.00426	$2.29X10^{-6}$
2	0.00419	0.00149
1 or 2	0.00373	$4.96X10^{-4}$
2	0.00316	$1.20X10^{-7}$
2	0.00131	0.00141
2	$3.37X10^{-4}$	0.00681
1	$1.08X10^{-4}$	$4.01X10^{-8}$
1	$8.73X10^{-5}$	$2.29X10^{-6}$
2	$1.94X10^{-5}$	0.00211
1	$1.31X10^{-5}$	0.00211
1	$3.06X10^{-9}$	$2.13X10^{-7}$

Comment [JRC8]: Why does this jump 4 orders of magnitude smaller?

Figures V-4 and V-5 show doses to the MEI as a function of the fraction of shielding lost and as a function of distance from the cask.

Comment [JRC9]: See comments on these figures in Chapter V.

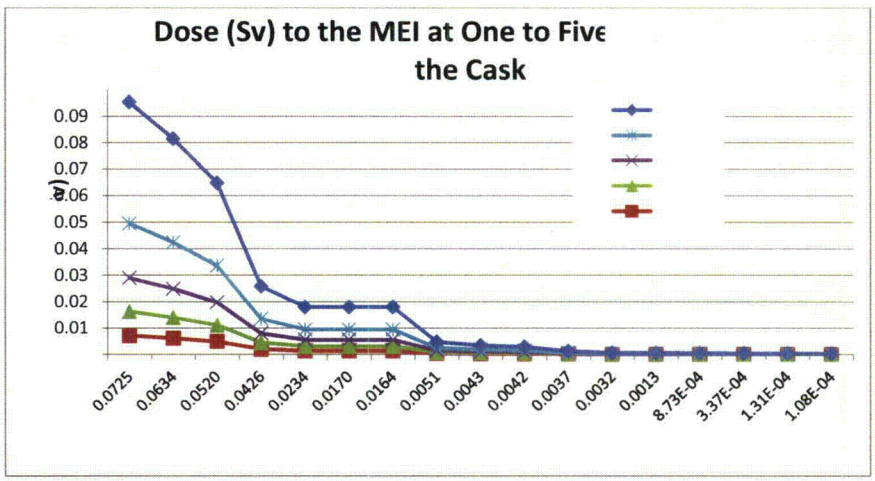

Figure V- 4. Dose to the MEI at various distances one to five meters from the cask.

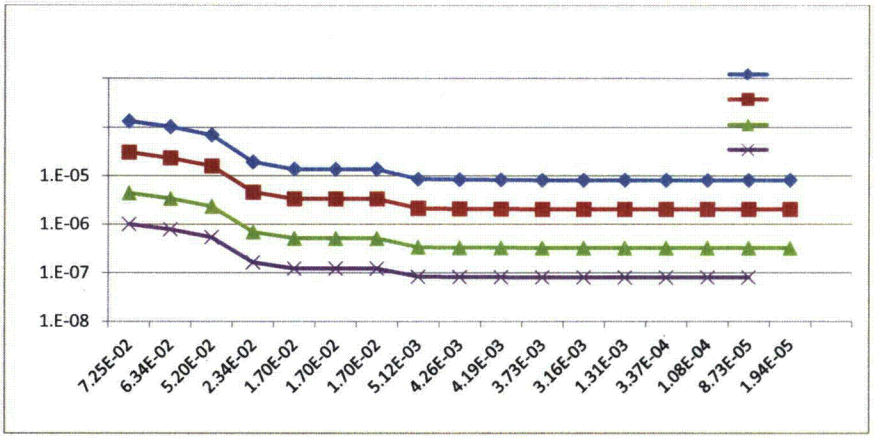

Figure V- 5. Dose to the MEI at various distances 10 to 100 m from the cask.

Table V-5 shows how the dose to the maximally exposed individual (MEI) depends on the fraction of the lead shield lost and distance from the cask, for a ten-hour exposure. Table V-5 includes both sides of the cask, since the doses are to an individual.

Comment [JRC10]: I think you meant Table V-4. Check all references to table numbers that follow.

Comment [JRC11]: Do you mean the individual is assumed to be equally exposed to both sides simultaneously, or is facing to the side with the greater shield loss plus some contribution from the other side?

The large doses that occur at near the cask (one to five meters from the cask) would be sustained by emergency responders, none of whom would spend all ten hours that close to the cask. The one- to five-meter doses can be considered occupational rather than public doses. If a loss-of-shielding accident occurred on a public right of way – a railroad track in this case – no member of the public would be closer than ten meters (30 feet). The public MEI dose (from the largest gap in the lead shield) would be 1.33 mSv (133 mrem), about 30% larger than the NRC standard for the public.

The "dose risk" combines the probability of a particular accident with the consequence (the dose). It is a risk, not a dose, and is much smaller than the dose. Tables V-6 a and b show the conditional dose risk, the combination of the conditional probability with the consequence, for each fractional loss of lead shielding. This is the risk of a particular accident scenario if there is an accident, and does not include the probability of an accident. The columns in Tables V-6 are in order of descending risk, with the greatest conditional dose risk at the top.

Table V-4. Radiation dose (Sv) to the MEI at various distances for the cask. The numbers in bold italics exceed the external dose rate of 10 CFR 71.51..

Fraction of lead lost	1 m	2 m	3 m	4 m	5 m	10 m	20 m	50 m
7.25E-02	***4.6E-02***	***2.1E-02***	***1.3E-02***	9.2E-03	7.1E-03	1.3E-04	3.1E-05	4.4E-06
6.34E-02	***3.9E-02***	***1.8E-02***	***1.1E-02***	7.9E-03	6.1E-03	1.0E-04	2.3E-05	3.4E-06
5.20E-02	***3.1E-02***	***1.4E-02***	8.7E-03	6.2E-03	4.8E-03	7.0E-05	1.6E-05	2.3E-06
2.34E-02	*1.2E-02*	5.6E-03	3.5E-03	2.5E-03	1.9E-03	1.9E-05	4.6E-06	6.9E-07
1.70E-02	8.6E-03	3.9E-03	2.4E-03	1.7E-03	1.3E-03	1.4E-05	3.3E-06	5.1E-07
1.70E-02	8.6E-03	3.9E-03	2.4E-03	1.7E-03	1.3E-03	1.4E-05	3.3E-06	5.1E-07
1.70E-02	8.6E-03	3.9E-03	2.4E-03	1.7E-03	1.3E-03	1.4E-05	3.3E-06	5.1E-07
5.12E-03	2.3E-03	1.0E-03	6.4E-04	4.6E-04	3.5E-04	8.5E-06	2.1E-06	3.4E-07
3.73E-03	1.6E-03	7.2E-04	4.5E-04	3.3E-04	2.5E-04	8.3E-06	2.1E-06	3.3E-07
3.16E-03	1.3E-03	6.1E-04	3.8E-04	2.8E-04	2.1E-04	8.2E-06	2.1E-06	3.3E-07
1.31E-03	5.7E-04	2.6E-04	1.7E-04	1.2E-04	9.5E-05	8.1E-06	2.0E-06	3.2E-07
4.26E-04	2.6E-04	1.2E-04	8.0E-05	5.9E-05	4.6E-05	8.1E-06	2.0E-06	3.2E-07
4.19E-04	2.6E-04	1.2E-04	7.9E-05	5.8E-05	4.6E-05	8.1E-06	2.0E-06	3.2E-07
3.34E-04	2.3E-04	1.1E-04	7.2E-05	5.3E-05	4.2E-05	8.1E-06	2.0E-06	3.2E-07
1.08E-04	1.6E-04	8.1E-05	5.3E-05	4.0E-05	3.2E-05	8.1E-06	2.0E-06	3.2E-07
8.73E-05	1.6E-04	7.8E-05	5.2E-05	3.9E-05	3.1E-05	8.1E-06	2.0E-06	3.2E-07
1.94E-05	1.4E-04	7.2E-05	4.8E-05	3.6E-05	2.9E-05	8.1E-06	2.0E-06	3.2E-07

Comment [JRC12]: How is the dose being compared to the dose rate? – based on 10hr exposure?

Comment [JRC13]: Row repeated? In Figures V-4 and V-5 as well?

Comment [JRC14]: Row re-repeated?

Table V-5. The "conditional dose risk," the product of dose and conditional probability, in Sv to the maximally exposed individual at distances from the cask from one to five meters.

Conditional Probability	Distance from the cask (m)				
	1	2	3	4	5
8.03E-08	3.7E-09	1.6E-09	1.0E-09	7.4E-10	5.7E-10
2.41E-07	9.4E-09	4.2E-09	2.6E-09	1.9E-09	1.5E-09
2.41E-07	7.5E-09	3.3E-09	2.1E-09	1.5E-09	1.2E-09
7.63E-07	9.5E-09	4.2E-09	2.7E-09	1.9E-09	1.5E-09
1.49E-03	1.3E-05	5.7E-06	3.6E-06	2.6E-06	2.0E-06
4.58E-06	3.9E-08	1.8E-08	1.1E-08	7.9E-09	6.1E-09
4.58E-06	3.9E-08	1.8E-08	1.1E-08	7.9E-09	6.1E-09
2.29E-06	5.1E-09	2.3E-09	1.5E-09	1.0E-09	8.1E-10
1.94E-05	3.1E-08	1.4E-08	8.8E-09	6.3E-09	4.9E-09
8.73E-05	1.2E-07	5.3E-08	3.3E-08	2.4E-08	1.9E-08
1.08E-04	6.2E-08	2.8E-08	1.8E-08	1.3E-08	1.0E-08
1.49E-03	3.8E-07	1.8E-07	1.2E-07	8.7E-08	6.9E-08
4.96E-04	1.3E-07	6.1E-08	3.9E-08	2.9E-08	2.3E-08
3.37E-04	7.7E-08	3.7E-08	2.4E-08	1.8E-08	1.4E-08
1.31E-03	2.2E-07	1.1E-07	7.0E-08	5.2E-08	4.2E-08
3.16E-03	5.0E-07	2.5E-07	1.6E-07	1.2E-07	9.8E-08
3.73E-03	5.3E-07	2.7E-07	1.8E-07	1.3E-07	1.1E-07

Comment [JRC15]: Row repeated.

Table V-6. The "conditional dose risk," the product of dose and conditional probability, in Sv to the maximally exposed individual at distances 10 to 100 meters from the cask.

Conditional Probability	Distance from the cask (m)			
	10	20	50	100
8.03E-08	1.1E-11	2.4E-12	3.5E-13	8.0E-14
2.41E-07	2.5E-11	5.6E-12	8.1E-13	1.9E-13
2.41E-07	1.7E-11	3.9E-12	5.6E-13	1.3E-13
7.63E-07	1.5E-11	3.5E-12	5.2E-13	1.3E-13
1.49E-03	2.0E-08	4.9E-09	7.5E-10	1.8E-10
4.58E-06	6.3E-11	1.5E-11	2.3E-12	5.6E-13
4.58E-06	6.3E-11	1.5E-11	2.3E-12	5.6E-13
2.29E-06	1.9E-11	4.9E-12	7.7E-13	1.9E-13
1.94E-05	1.6E-10	4.0E-11	6.4E-12	1.6E-12
8.73E-05	7.2E-10	1.8E-10	2.9E-11	7.1E-12
1.08E-04	8.7E-10	2.2E-10	3.5E-11	8.7E-12
1.49E-03	1.2E-08	3.0E-09	4.8E-10	1.2E-10
4.96E-04	4.0E-09	1.0E-09	1.6E-10	4.0E-11
3.37E-04	2.7E-09	6.8E-10	1.1E-10	2.7E-11
1.31E-03	1.1E-08	2.7E-09	4.2E-10	1.1E-10
3.16E-03	2.5E-08	6.4E-09	1.0E-09	2.5E-10
3.73E-03	3.0E-08	7.5E-09	1.2E-09	3.0E-10

The collective dose risk to an exposed population within a radius *r* of the cask may be calculated by equation (V-1)

(V-1)

where A is the accident frequency on the route segment under consideration
r is the distance from the cask: 20, 50, 100 and 800 meters
$0.5\pi r^2$ is the area of the semicircle of people around the cask
PD is the population density per km^2 in the semicircle
D_{avi} is the average individual dose from the ith fractional loss of shielding
P_{ci} is the conditional probability of the ith fractional loss of shielding.

The index *i* indicates a particular fractional shielding loss; these are summarized above in Table V-3. The population at the shielding loss accident is exposed to only one side of the cask. Thus this analysis assumed that half of this population would be exposed to each side of the cask, so that dose risks were calculated separately for exposure to each side of the cask. The summation in equation (V-1) is the conditional dose risk of all of the accidents considered: the "universe" of accidents. Table V-7 shows collective conditional dose risks for the sixteen routes analyzed.

Deleted: along the route

Comment [JRC16]: Table needs totals for sides and routes.

Table V-7. Collective conditional dose risks due to loss of lead shielding in person-Sv in a semicircular area of radius 100 meters around the cask.

Comment [JRC17]: Why not 800 meters?

		Side 1				Side 2			
		ORNL	DEAF SMITH	HANFORD	SKULL VALLEY	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	Rural	9.37E-10	6.91E-10	1.10E-09	8.57E-10	5.09E-09	3.75E-09	5.99E-09	4.66E-09
	Suburb	1.78E-08	1.91E-08	1.77E-08	1.72E-08	9.58E-08	1.03E-07	9.49E-08	9.22E-08
	Urban	1.93E-09	1.99E-09	1.86E-09	1.55E-09	1.03E-08	1.07E-08	1.00E-08	8.34E-09
KEWAUNEE	Rural	9.37E-10	4.61E-10	4.62E-10	5.91E-10	5.09E-09	2.50E-09	2.51E-09	3.21E-09
	Suburb	1.92E-08	2.03E-08	1.78E-08	2.08E-08	1.03E-07	1.09E-07	9.54E-08	1.12E-07
	Urban	2.10E-09	2.10E-09	1.94E-09	1.74E-09	1.13E-08	1.13E-08	1.04E-08	9.36E-09
INDIAN POINT	Rural	7.96E-10	5.72E-10	5.66E-10	6.63E-10	4.32E-09	3.11E-09	3.07E-09	3.60E-09
	Suburb	2.40E-08	1.98E-08	1.89E-08	2.02E-08	1.29E-07	1.06E-07	1.01E-07	1.08E-07
	Urban	2.56E-09	2.19E-09	2.12E-09	1.94E-09	1.37E-08	1.18E-08	1.14E-08	1.04E-08
IDAHO NATIONAL LAB	Rural	5.80E-10	2.40E-10	3.01E-10	5.99E-10	3.15E-09	1.30E-09	1.63E-09	3.26E-09
	Suburb	2.02E-08	2.01E-08	2.02E-08	1.97E-08	1.09E-07	1.08E-07	1.08E-07	1.06E-07
	Urban	1.70E-09	1.56E-09	1.97E-09	2.08E-09	9.13E-09	8.37E-09	1.06E-08	1.11E-08

Population dose risk ultimately depends on the accident frequency as well as on the population along the route where the accident happens. The accident frequency, accidents per km, is equated to the accident probability. The rail accident frequencies used in this analysis are from DOT, 2008. Average railcar accident frequencies for each of the 16 routes are shown in Table V-8. These accident frequencies are combined with the average dose risk integrated over the potentially exposed population.

Table V-9 shows the collective dose risks to populations on each side of the rail cask that has lost lead shielding on impact. These estimates include both the conditional probabilities and the accident frequencies on each route, as in Equation (V-1). Thus the differences in Table V-9 are due to differences in traffic accident frequencies.

Table V-8. Average railcar accident frequencies on the routes studied.

ORIGIN	DESTINATION	AVERAGE ACCIDENTS PER KM
MAINE YANKEE	ORNL	6.5×10^{-7}
	DEAF SMITH	5.8×10^{-7}
	HANFORD	4.2×10^{-7}
	SKULL VALLEY	5.1×10^{-7}
KEWAUNEE	ORNL	4.3×10^{-7}
	DEAF SMITH	3.3×10^{-7}
	HANFORD	2.4×10^{-7}
	SKULL VALLEY	3.7×10^{-7}
INDIAN POINT	ORNL	8.8×10^{-6}
	DEAF SMITH	6.2×10^{-7}
	HANFORD	5.1×10^{-7}
	SKULL VALLEY	5.5×10^{-7}
INL	ORNL	3.6×10^{-7}
	DEAF SMITH	3.5×10^{-7}
	HANFORD	3.2×10^{-7}
	SKULL VALLEY	2.8×10^{-7}

Table V-9. Conditional collective dose risks per shipment (person-Sv) from loss of lead shielding, including conditional probabilities

ORIGIN	TYPE	Side 1				Side 2			
		ORNL	DEAF SMITH	HANFORD	SKULL VALLEY	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE	Rural	3.09E-12	1.35E-12	1.97E-12	9.31E-13	1.70E-11	7.44E-12	1.09E-11	5.13E-12
	Subu	5.87E-11	3.74E-11	3.16E-11	1.87E-11	3.19E-10	2.03E-10	1.72E-10	1.02E-10
	U	6.34E-12	3.89E-12	3.33E-12	1.69E-12	3.45E-11	2.12E-11	1.81E-11	9.18E-12
KEWAUNEE	R	1.22E-12	2.87E-13	3.06E-13	3.06E-13	6.74E-12	1.58E-12	1.69E-12	1.69E-12
	S	2.51E-11	1.26E-11	1.18E-11	1.07E-11	1.36E-10	6.86E-11	6.40E-11	5.85E-11
	U	2.74E-12	1.31E-12	1.28E-12	9.01E-13	1.49E-11	7.11E-12	6.98E-12	4.90E-12
INDIAN POINT	R	3.36E-11	1.09E-12	1.15E-12	4.62E-13	1.85E-10	6.02E-12	6.34E-12	2.55E-12
	S	1.01E-09	3.78E-11	3.83E-11	1.40E-11	5.49E-09	2.06E-10	2.08E-10	7.64E-11
	U	1.08E-10	4.18E-12	4.30E-12	1.35E-12	5.86E-10	2.27E-11	2.34E-11	7.36E-12
IDAHO N. L.	R	2.22E-13	1.61E-13	4.38E-14	5.56E-13	1.23E-12	8.87E-13	2.41E-13	3.07E-12
	S	7.75E-12	1.35E-11	2.94E-12	1.82E-11	4.22E-11	7.35E-11	1.60E-11	9.93E-11
	U	6.52E-13	1.05E-12	2.87E-13	1.92E-12	3.55E-12	5.69E-12	1.56E-12	1.05E-11

Comment [JRC18]: Clean-up entries.

V.3.1.2 Loss of lead shielding with fire

Lead melts at 330 °C, so that a prolonged high-temperature fire could result in lead slump, leaving a gap in the gamma shield which results in increased external radiation emission. In calculating doses from a loss of lead shielding, RADTRAN models a gap in the shield as an increase in the dose from a virtual radiation source (O'Donnell, et al., 2005; Dennis, et al., 2009). This is the same source as the basis for the incident-free transportation model (Figure II.1, Appendix II).

Deleted: Release of radioactive materials in a fire depends on the offset of the cask from the fire.¶

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The loss of lead shielding does not occur during a fire. Lead expands as it melts and can buckle the innermost cask shell. When the melted lead cools and solidifies, it occupies the same volume as before expansion but the volume available between the steel cask shells is larger because of the buckling of the inner shell, leaving a gap. Melting of lead and the formation of a gap in the lead are described fully in Appendix IV. Briefly, if the cask is offset from the fire, the gap would be in the section of lead shield facing the fire. In an engulfing fire, the gap would be at the upper surface of the cask. However, if the cask is turned after the melted lead has solidified; the gap in the lead would be on the side of the cask rather than at the top. Thus, in both cases, anyone facing the side of the cask with the shielding gap could sustain an increased radiation dose.

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Two accidental fire scenarios can result in a loss of lead shielding:

- Fire Scenario 1: a sufficiently hot pool fire engulfing a cask on the ground can melt enough lead in three hours to create an 8.14 percent fractional shield loss.
- Fire Scenario 2: a sufficiently hot pool fire offset from the cask, burning for more than three hours, can create a 2.01 percent fractional shield loss.

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These scenarios are described fully in Appendix IV. The doses sustained by the maximally exposed individual at various distances from the cask, exposed for an hour, are shown in Table V-10.

Table V-10. Radiation dose (Sv) to the maximally exposed individual at various distances from a cask that has been in a fire.

Fraction of lead lost	1 m	2 m	5 m	10 m	20 m	50 m	100 m
0.0201	7.0E-03	3.1E-03	1.1E-03	1.1E-05	2.6E-06	3.9E-07	9.4E-08
0.0814	3.5E-02	1.6E-02	5.4E-03	1.1E-04	2.6E-05	3.7E-06	8.5E-07

No lead shielding would be lost until the fire was out and the cask had cooled enough for the lead to solidify, since only then would there be a gap in the lead shield. Thus no one would be exposed for many hours after the accident, and with a fire this severe, nearby residents and the public would probably have been evacuated. The maximally exposed individual in this case would be an emergency responder. Under these circumstances, measures could be taken to mitigate emergency responder exposures.

Volpe (2006, Figure 16) postulates a chain of events leading to a fire, from which the probability of these scenarios can be calculated. The relevant portion of the Volpe figure is shown in Figure V-6.

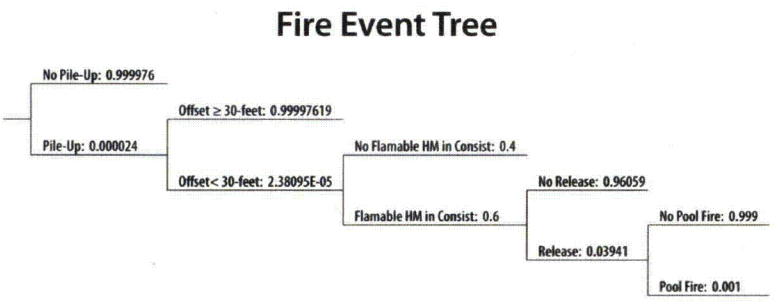

Figure V-6. Event tree branch for a rail fire accident (from Volpe, 2006, Figure 16)

The first of these events is a major derailment, as shown in Table V-11. Volpe estimates that the speed at the time of the accident for such a derailment is at least 80 km/hr (50 mph). If a pileup could occur in any kind of derailment other than in a tunnel, from Figure V-2, the probability of such a major derailment is

$$(0.7355)*(0.0155)*(0.06614+0.00061)*(0.0011+0.0004+0.0077+.0113) = 1.56 \times 10^{-5}$$

Table V-11 lists the other events in the scenario, together with the probability of each event. These events are a pileup, a flammable hazardous cargo within 10 meters (about half a rail-car length), leaking of that hazardous substance, and ignition of a pool fire. The net probability of the sequence of events shown in Table V-11 following a major pileup is 1.35×10^{-14}. However, Volpe's rationale for the pileup probability of 2.4×10^{-5} is not as robust as for the other probabilities. Using the "no pileup" branch, the net probability for the events of Table V-11 is 5.6×10^{-10}.

Comment [JRC19]: Unclear. What exactly do you mean? Volpe value is incorrect by 5 orders of magnitude, and is being ignored; yet Volpe-derived value is used instead? Has Volpe been contacted on this point?

Thus the conditional probability of Fire Scenario 1, a major derailment leading to a three-hour pool fire that surrounds the cask is then

$$(1.56 \times 10^{-5})*(5.6 \times 10^{-10}) = 8.8 \times 10^{-15}$$

The conditional probability of Fire Scenario 2, a major derailment leading to a three-hour fire offset from the cask by more than 10 meters is then

$$(1.56 \times 10^{-5})*(2.36 \times 10^{-5}) = 3.7 \times 10^{-10}$$

Table V-11. Events leading to a train fire that could involve a spent fuel cask

EVENT	PROBABILITY	ALTERNATIVE EVENT	PROBABILITY
Major high speed derailment	1.56×10^{-5}	No major derailment	0.99999
Pileup	2.4×10^{-5}	No pileup	0.99998
Offset < 10 m	2.38×10^{-5}	Offset >10 m	0.99998
Flammable hazardous material in another railcar	0.6	No flammable material available	0.4
Release of flammable material	0.0394	No release of flammable material	0.9606
Pool fire	0.001	No pool fire	0.999

The average accident frequency for the 16 rail routes studied is 3.9×10^{-3} (the range is from 1.5×10^{-4} to 4.2×10^{-2}). Thus, the average probability of an accidental fire that could cause loss of lead shielding in a rail cask is 3.4×10^{-19} if the cask is concentric with the fire and 1.4×10^{-14} if the cask and fire are offset by 10 meters or more. The largest dose risk would be 4.9×10^{-17} Sv.

V.3.2 Loss of Neutron Shielding

The neutron shield is usually a hydrocarbon or carbohydrate polymer, sometimes borated, since boron and organic polymers are good neutron absorbers. Neutron shielding burns, and could be destroyed in a fire. The neutron dose from loss of shielding in a fire is estimated using the parameters listed in Table V-12. The conditional probability of a truck fire is from Figure V-1. The conditional probability of a rail fire is a combination of the fire probability in Figure V-2 and the following steps from Figure V-5.

Comment [JRC20]: How are effects of fire on gamma shielding and neutron shielding combined in the analysis? I assume a fire that melts lead would burn an organic polymer?

- A pileup
- Flammable cargo on the train
- Release of the flammable cargo

The neutron TI for the Truck-DU cask is from General Atomics, 1998; the TI for the Rail-Pb cask, from NAC International, 2002; and the TI for the Rail-Steel cask, from Holtec International, 2004. The RADTRAN external dose rate is modeled as entirely neutron emission. The other parameters are the same as those used in calculating doses from an accident in which there is no release of radioactive material and no loss of lead shielding (Chapter 5, Section 5.4).

Table V-12. Some parameters used in calculating loss of neutron shielding.

Parameter	Truck-DU	Rail-Pb	Rail-Steel
Conditional probability of a fire	0.0063	8.9×10^{-8}	8.9×10^{-8}
Dose rate at one meter from the cask in mSv/hour (mrem/hour)	1.78 (178)	1.81 (181)	1.82 (182)
Shielding of residents.	none	none	none
Time until the cask is removed (hours)	10	10	10

The neutron doses to emergency responders (five meters from the cask) are shown in Table V-13, the collective doses on the 16 routes are shown in Table V-14, and the total collective dose risks, including accident frequency, are shown in Table V-15.

Table V-13. Doses to an emergency responder five meters from the cask.

Cask	Dose in Sv	Ten-hour 10 CFR 71.51 dose in Sv
Truck-DU	0.00729	1.00
Rail-Pb	0.00761	1.00
Rail-Steel	0.00763	1.00

Comment [JRC21]: Complete loss of neutron shielding? Why so many distances molded for gamma, but not neutron?

Comment [JRC22]: I find no such dose limit in 71.51.

Table V-14. Collective doses (consequences) to an emergency responder? in person-Sv from loss of neutron shielding.

FROM	TO	Truck-DU	Rail-Pb	Rail-Steel
MAINE YANKEE	ORNL	7.49E-04	7.17E-04	7.40E-04
	DEAF SMITH	7.01E-04	6.71E-04	6.93E-04
	HANFORD	6.23E-04	5.96E-04	6.15E-04
	SKULL VALLEY	6.38E-04	6.11E-04	6.31E-04
KEWAUNEE	ORNL	6.87E-04	6.57E-04	6.78E-04
	DEAF SMITH	6.41E-04	6.13E-04	6.33E-04
	HANFORD	5.98E-04	5.72E-04	5.91E-04
	SKULL VALLEY	6.17E-04	5.91E-04	6.10E-04
INDIAN POINT	ORNL	7.28E-04	6.97E-04	7.20E-04
	DEAF SMITH	6.95E-04	6.65E-04	6.87E-04
	HANFORD	6.38E-04	6.11E-04	6.31E-04
	SKULL VALLEY	6.63E-04	6.34E-04	6.55E-04
INL	ORNL	5.78E-04	5.53E-04	5.71E-04
	DEAF SMITH	6.16E-04	5.89E-04	6.08E-04
	HANFORD	3.78E-04	3.62E-04	3.73E-04
	SKULL VALLEY	6.41E-04.	6.13E-04	6.33E-04

Table V-15. Collective dose risks in person-Sv from loss of neutron shielding.

FROM	TO	Truck-DU	Rail-Pb	Rail-Steel
MAINE YANKEE	ORNL	4.7E-06	6.4E-11	6.6E-11
	DEAF SMITH	4.4E-06	6.0E-11	6.2E-11
	HANFORD	3.9E-06	5.3E-11	5.5E-11
	SKULL VALLEY	4.0E-06	5.4E-11	5.6E-11
KEWAUNEE	ORNL	4.3E-06	5.8E-11	6.0E-11
	DEAF SMITH	4.0E-06	5.5E-11	5.6E-11
	HANFORD	3.8E-06	5.1E-11	5.3E-11
	SKULL VALLEY	3.9E-06	5.3E-11	5.4E-11
INDIAN POINT	ORNL	4.6E-06	6.2E-11	6.4E-11
	DEAF SMITH	4.4E-06	5.9E-11	6.1E-11
	HANFORD	4.0E-06	5.4E-11	5.6E-11
	SKULL VALLEY	4.2E-06	5.6E-11	5.8E-11
INL	ORNL	3.6E-06	4.9E-11	5.1E-11
	DEAF SMITH	3.9E-06	5.2E-11	5.4E-11
	HANFORD	2.4E-06	3.2E-11	3.3E-11
	SKULL VALLEY	4.0E-06	5.5E-11	5.6E-11

V.4 Release of Radioactive Materials in Accidents

V.4.1 Spent Fuel Inventory

A Rail Pb-cask is the only cask studied that would release any radioactive material in an accident. Since there is no traffic accident that would result in a release from the Truck-DU or Rail-Steel cask, the inventory of those casks is not relevant to this analysis. The fuel used in this analysis is PWR fuel, 45,000 MWD/MTU burnup, the maximum burnup that a Rail-Pb cask would transport, and has cooled for nine years before transport. The radionuclide inventory of this fuel was determined using ORIGEN (Croff, 1980).[2] The radionuclide activities in the inventory were "normalized" by dividing each activity by the A_2 value for that radionuclide. The A_2 value—the amount of the radionuclide that could be transported in a Type A container, is an indication of the radiotoxicity; the larger the A_2 value, the smaller the radiotoxicity of that nuclide. The normalized radioactivities were then sorted and added until 99.99 percent of the total normalized radioactivity was reached.[3] The radionuclides selected this way are listed in Table V-16, together with their actual radioactivities (not the normalized radioactivities).

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Comment [JRC23]: Does this footnote belong in Acknowledgements section?

Comment [JRC24]: In the Q system, from which the A values are derived, it is (basically) assumed that only 1% of the Type A package contents are released, and only 1% of the released material is inhaled/ingested, etc.

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Comment [JRC25]: Explain why you do this.

[2] The preparers are indebted to J.D. Smith of Sandia National Laboratories for the ORIGEN run.

[3] The "total normalized activity" referred to here is not the total A_2 value as calculated by the formula in 10 CFR Part 71 Appendix A.

Table V-16. TBq inventory for the Rail-Pb cask. The ^{60}Co inventory is estimated CRUD.

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Radionuclide	TBq
	26 Assemblies
^{240}Pu	2.20E+05
^{239}Pu	5.16E+03
^{137}Cs	1.23E+06
^{238}Pu	2.02E+03
^{243}Cm	7.04E+02
^{60}Co	3.39E+04
^{154}Eu	2.53E+04
^{134}Cs	1.13E+04
^{85}Kr	6.36E+04
^{241}Am	4.45E+00
^{242}Cm	2.81E+01
^{155}Eu	7.38E+03
^{231}Pa	8.77E-01
^{106}Ru	2.11E+02
^{236}U	5.39E+00
^{233}U	2.53E+04
^{241}Pu	1.62E+01
^{113m}Cd	1.72E+01

V.5.3 Dispersion of Released Radionuclides

If a spent fuel cask transportation accident did result in the release of radioactive material, the public could be exposed if the material was dispersed through the air. Experimental work reviewed by Sprung et al (2000, pp.7-30 et seq) indicates that only very small particles with analytic mean aerodynamic diameter (AMAD)[4] ten microns or less would be released from a cask in an accident, because the only release path is through the seals at the ends of the cask. In addition, particles larger than this are filtered by larger particles inside the cask. Ten microns is generally considered the upper limit of respirability. Thus particles accidentally released from a cask will be released as a respirable aerosol.

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The discussion below is an abbreviated discussion of air dispersion, a subject that is treated extensively and in detail in textbooks like Wark and Warner (1981).

The basic equation for atmospheric dispersion of an aerosol is the Gaussian dispersion equation: Equation (V.2) (Turner, 1994, Chapter 2).

$$\frac{CHI}{Q} = \frac{1}{2\pi u \sigma_y \sigma_z} \exp\left[\frac{-y^2}{2\sigma_y^2}\right] \exp\left[\frac{-z^2}{2\sigma_z^2}\right] \qquad \text{(V-2)}$$

[4] The AMAD is the diameter of a sphere of density 1 gm/cm^3 that has the same inertial properties as the actual particle.

where CHI[5] = the concentration of particles in the air
Q = the radioactivity or mass of airborne particles
u = the wind speed
σ_y, σ_z are meteorological constants and are functions of the downwind distance x.

The wind direction is traditionally along the x axis of a Cartesian coordinate system, the crosswind direction is y, and z represents the altitude above ground. When the plume of released material rises buoyantly to a height H, the Gaussian equation becomes

(V-3)
$$\frac{CHI}{Q} = \frac{1}{2\pi u \sigma_y \sigma_z}$$

where H is the height to which the plume rises before being blown downwind. For a ground-level release along the plume centerline, Equations (V.2) and (V.3) reduce to

(V-4)
$$\frac{CHI}{Q} = \frac{1}{2\pi u \sigma_y \sigma_z} \exp\left[\frac{-y^2}{2\sigma_y^2}\right] \exp\left[\frac{-H^2}{2\sigma_z^2}\right]$$

Radioactive gases released in accident will disperse in the air according to Equations (V.1) and (V.3). Particles, however, have mass and will settle on the ground. The settling velocity V_t—the terminal velocity of a particle in the indicated size range—is given by Equation (V.5)

(V-5)

where g = gravitational acceleration
d = particle aerodynamic diameter
ρ = particle density
μ = air viscosity at ambient temperature

Ground deposition rate is then described by Equation (V.6) (Wark and Warner, 1981, Chapter 5)'

(V-6)
$$\frac{w_p}{Q} = \frac{V_t}{2\pi u \sigma_y \sigma_z} \exp\left[\frac{-y^2}{2\sigma_y^2}\right] \exp\left[\frac{-\left(H - \frac{xV_t}{u}\right)^2}{2\sigma_z^2}\right]$$

[5] The Greek letter X is traditionally used to represent air concentration, but is so easily confused in typescript with the 24th letter of the alphabet that it is often written phonetically ("chi").

where w_p is the particle deposition rate. These equations are programmed in RADTRAN.

Both wind and air temperature profiles affect the dispersion of airborne material. The predominant motion of airborne material is downwind, while crosswind motion is diffusive. Light winds, stable air, and temperature inversions result in less dispersion and higher airborne and ground concentrations of radionuclides. Strong winds and turbulent air are good conditions for dispersion and result in lower airborne and deposited radionuclides concentration and consequently result in lower radiation doses to the public, even though the plume of radioactive material may spread over a large area.

RADTRAN calculates external doses from deposited material ("groundshine") and from material that remains suspended in the air ("cloudshine"). The code also calculates internal committed doses from airborne material that is inhaled, and from material that becomes resuspended in the air. The doses reported are the sums of the groundshine, cloudshine, inhaled, and resuspended inhaled doses, unless otherwise indicated. Adding these doses to sum to a "total effective dose equivalent" is NRC practice in determining public exposure, as discussed in 10 CFR 20.1301. RADTRAN accommodates a number of atmospheric dispersion conditions.

V.5.4 Release fractions

Release of radionuclides into the environment from a cask depends on releases from the fuel rods into the cask and from the cask to the environment. If the cask contains canistered fuel, the cask structural analysis in Chapter 4 shows that the canister does not rupture even under the most severe accidents analyzed, so no radioactive material can exit the cask. In the present study, therefore, only the NAC-STC transporting uncanistered could release any radioactive material or CRUD as a consequence of a traffic accident. Only PWR spent fuel is considered in this section.

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V.5.4.1 CRUD

Radioactive material available for release comes from both spent fuel and Chalk River Unidentified Deposits (CRUD). CRUD is a corrosion product that forms on the outside of the fuel rods; its source is not the fuel rod inventory but other metallic structures in the reactor. In a PWR reactor its radioactive constituents are ^{60}Co, ^{58}Co, ^{54}Mn, ^{51}Cr, ^{59}Fe, ^{95}Zr, ^{125}Sb, and ^{65}Zn. ^{60}Co is the only CRUD constituent sufficiently long-lived to be part of any accidental release. Although CRUD deposits on the outside of fuel rods, cask seals would have to be breached for CRUD to be released. Thus the only cask from which CRUD would be released in an accident is the NAC-STC. Sprung, et al (2000, Page 7-49) and Hanson et al (2010) estimate the amount of CRUD per fuel rod for PWR and BWR spent fuel. The estimates include the following assumptions:

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- CRUD forms on the outside rods of the assemblies
- Thirteen percent of the rod area is covered with a CRUD layer. The layer is between 33 and 100 microns thick. The total amount of CRUD was thus assumed to be 8.5 microns thick over the entire surface of the outside rods. The density of the CRUD layer was assumed to be one gram per cm^3 for the CRUD that could be airborne in the cask (Einziger and Beyer, 2007)
- CRUD was assumed to be entirely ^{60}Co, and the activity was calculated using Equation (V-7).

(V-7)

Einziger and Beyer estimate that, with certain conservative assumptions, about 15 percent of the CRUD formed could remain airborne in the cask and available to be swept from the cask in the event of cask depressurization. Using these estimates, the CRUD activity in the NAC-STC would be:

- 268 TBq (7075 Ci) in a cask carrying twenty-six 17x17 PWR assemblies

And the airborne fraction in the cask would be 40.2 TBq (1061 Ci). If fuel rods are undamaged, no CRUD would be released in an accident because there would be no depressurization even if the cask seals are compromised. If fuel rods are damaged, material from the spent fuel will be released along with CRUD. Therefore, there is no accident in which only CRUD would be released.

Comment [JRC27]: If the accident is so severe that the seals are compromised, do you believe the fuel would be undamaged? Do we need to consider this scenario?

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The fraction of airborne particles that could be swept from the cask depends on the pressure differential between the cask and the environment:

$$F_{CE} = (1 - f_{deposited})(p_{atm}/p_{inp}) \qquad \text{(V-6)}$$

Where F_{CE} is the fraction released from the cask to the environment, $f_{deposited}$ is the fraction of airborne material in the cask deposited on its inner surface, p_{atm} is the atmospheric pressure and p_{inp} is the cask internal pressure. The only release path that would be available is through the seals at the end of the cask. Therefore, $p_{atm}/p_{inp} = 0.667$. From Figure 7.5 of Sprung et al (2000), about one percent of the 15 percent of the CRUD that has spalled from the rods, or about 0.15 percent, would be respirable (10 microns or less aerodynamic diameter). Thus, from Equation (V-6) the fraction of CRUD that would be released is 0.001. The dose calculations done with RADTRAN applied the 15 percent to the ^{60}Co inventory and the other factors to the release fraction.

V.5.4.2 Spent Fuel Radionuclides

When fuel rods are fractured in an impact, they depressurize rapidly, and the consequent overpressure sweeps fuel particles out of the cask if there is a breach in the seal. The depressurization and release of material from the rod is described very clearly in Hanson, et al, 2008,

> *When commercial spent nuclear fuel (CSNF) is handled in a dry environment, whether as fuel assemblies, canned, or within a container, one possible mechanism for radionuclide release is from oxidation of the CSNF exposed to air.... in a drop accident scenario, it is possible that the cladding could fracture, and cans or containers could breach, allowing oxygen to contact the fuel (Sprung et al. 2000). Upon clad breach, it is expected that the rod would rapidly depressurize, releasing its fill gas (e.g., He) and fission gases (e.g., Kr, Xe) that have been released from the fuel matrix, depending on the size of the cladding defect and fuel burnup characteristics (Einziger and Beyer 2007..... It is also possible for fuel fines to be ejected as the high-pressure fill and fission gases rapidly escape through the defect. As the fuel oxides and forms U_3O_8, it swells and causes further clad unzipping, potentially releasing the fine-powdered U_3O_8 and allowing additional fission gas release.(Hanson, et al, 2008, Section 1)*

These authors examined the behavior of relatively high burnup fuel. The release fractions from the rods to the cask, under the described conditions, are developed from the data of Hanson, et al for 45

GWD/MTU spent fuel. Einziger (2007) describes the formation of a rim on the fuel pellet that has a higher porosity that the body of the pellet. This porosity results ion reduced hardness of the pellet (Hanson et al, Figures 1.6 and 1.7)). However, the pellet rim is toughened by grain refinement, suggesting that release of fine particles from the fuel rods could be smaller than releases from lowerburnup fuel. Figure V-6 shows the difference between a rim and the pellet interior.

Comment [JRC28]: Font size shift begins here?

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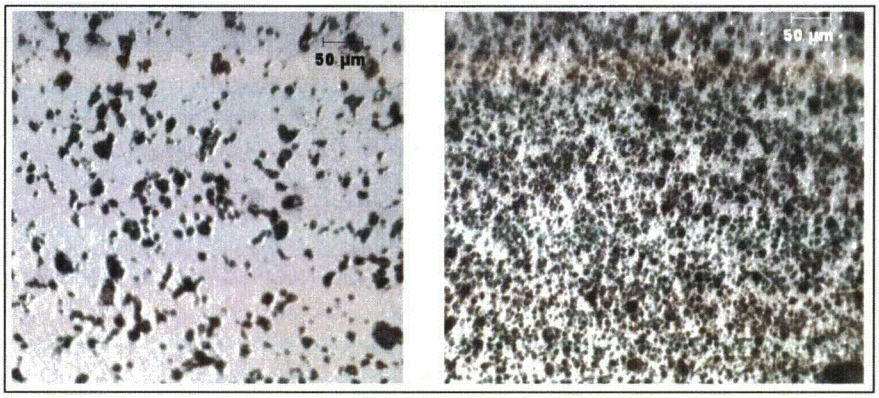

Figure V-6. Electron micrographs of the fuel pellet interior (left-hand picture) and the fuel pellet rim (right-hand picture). (Courtesy of Dr. R. E. Einziger, NRC)

Figure 1.10 of Hanson et al. suggests a release fraction for fission gases (^{85}Kr in the fuel in this analysis) of 0.5 percent. These authors suggest that volatile fission products like ^{137}Cs and ^{134}Cs exhibit release behavior like fission gases. However, cesium would be released as the oxide or chloride, and would therefore behave more like particulate matter than like fission gases. Because the volatiles tend to migrate to the fuel rim and Einziger (2007) recommends 3 x 10^{-5} as an appropriate release fraction for rim material, this release fraction is for volatiles in the present analysis. Ruthenium was grouped with cesium as a volatile.

Comment [JRC29]: Check – reads choppy – something missing at end?

Hanson et al. describe a number of mechanical tests performed on unoxidized fuel of varying burnup. Page 4.12 of Hanson et al. summarizes release fractions from these tests for the fuel that appears to be the most appropriate. A release fraction of 4.8 x 10^{-6} is used in this analysis for release of fine particles from the rod to the cask.

Comment [JRC30]: You imply, but do not state, that the selection of the release fraction is based on consideration of Hanson's work?

Figure 7.11 of Sprung et al (2000) presents release fractions of several compounds as functions of the available leak area. The compounds studied represent the physical/chemical groups present in spent nuclear fuel: gas, volatiles, and particulate matter. This figure served as the basis for estimating the cask-to-environment release fractions of the physical/chemical groups studied.

Table V-17 summarizes the parameters from which release fractions were developed.

Table V-17. Parameters for determining release functions for the accidents that would result in release of radioactive material.

	Cask Orientation	End	Corner	Side	Side	Side	Side	Corner
	Impact Speed (kph)	193	193	193	193	145	145	145
	Seal	metal	metal	elastomer	metal	elastomer	metal	metal
Cask to Environment Release Fraction	Gas	0.800	0.800	0.800	0.800	0.800	0.800	0.800
	Particles	0.70	0.70	0.70	0.70	0.70	0.70	0.64
	Volatiles	0.50	0.50	0.50	0.50	0.50	0.50	0.45
	Crud	0.001	0.001	0.001	0.001	0.001	0.001	0.001
Rod to Cask Release Fraction	Gas	0.005	0.005	0.005	0.005	0.005	0.005	0.005
	Particles	4.80E-06	4.80E-06	4.80E-06	4.80E-06	4.80E-06	4.80E-06	2.40E-06
	Volatiles	3.00E-05	3.00E-05	3.00E-05	3.00E-05	3.00E-05	3.00E-05	1.50E-05
	Crud	1.00	1.00	1.00	1.00	1.00	1.00	1.00
	Conditional Probability	2.68E-08	1.61E-07	8.02E-08	8.02E-08	8.02E-08	8.02E-08	3.06E-06

Comment [JRC31]: Should explain that this is this for combined rod-to-cask-to-environment?

The release from these potential accidents is not at ground level but at about 1.5 meters above ground, and the gas flowing from the cask is warmer than ambient, so that the plume of material will be lofted slightly, and the maximum air concentration and ground deposition would be at 21 meters downwind from the cask. The maximally exposed individual would be located at this point. Table V-14 estimates the radiation dose (consequence) that could result if radioactive material was released in a spent fuel cask accident. The total doses, 1.6 Sv and 0.73 Sv (160 rem and 73 rem), are significant but not acute or lethal.

Comment [JRC32]: No derivation for the 1.5 and 21 meter results? Perhaps shown somewhere else – reference?

Comment [JRC33]: Do you mean V-18

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Comment [JRC34]: Check this usage of acute – I thought acute pertained to the exposure timeframe, not significance.

Table V-18. Maximally exposed individual doses (consequences) in Sv from accidents that involve a release.

Cask Orientation	Impact Speed (kph)	Seal	Inhalation	Resuspension	Cloudshine	Groundshine	Total
End	193	metal	1.6E+00	1.4E-02	8.8E-05	9.4E-04	1.6E+00
Corner	193	metal	1.6E+00	1.4E-02	8.8E-05	9.4E-04	1.6E+00
Side	193	elastomer	1.6E+00	1.4E-02	8.8E-05	9.4E-04	1.6E+00
Side	193	metal	1.6E+00	1.4E-02	8.8E-05	9.4E-04	1.6E+00
Side	145	elastomer	1.6E+00	1.4E-02	4.5E-06	3.6E-05	1.6E+00
Side	145	metal	1.6E+00	1.4E-02	8.8E-05	9.4E-04	1.6E+00
Corner	145	metal	0.7270	0.0063	0.0001	0.0009	0.7340

When the doses in Table V-18 are multiplied by the probabilities in Table V-17, the "conditional dose risks" of Table V-19 result.

Table V-19 Maximally exposed individual conditional dose risks in Sv from accidents that involve a release.

Cask Orientation	Impact Speed (kph)	Seal	Inhalation	Resuspension	Cloudshine	Groundshine	Total
End	193	metal	4.26E-08	3.67E-10	2.35E-12	2.52E-11	4.29E-08
Corner	193	metal	2.56E-07	2.21E-09	1.41E-11	1.52E-10	2.58E-07
Side	193	elastomer	1.28E-07	1.10E-09	7.04E-12	7.55E-11	1.28E-07
Side	193	metal	1.28E-07	1.10E-09	7.04E-12	7.55E-11	1.28E-07
Side	145	elastomer	1.27E-07	1.10E-09	3.63E-13	2.90E-12	1.28E-07
Side	145	metal	1.28E-07	1.10E-09	7.04E-12	7.55E-11	1.28E-07
Corner	145	metal	2.22E-06	1.93E-08	1.57E-10	2.82E-09	2.25E-06

Population doses are calculated by integrating the rural, suburban, and urban population densities, respectively, over the largest plume footprint in the dispersion calculation: 1420 km^2 for neutral meteorological stability. Collective dose risks are calculated by multiplying each population dose by the appropriate conditional probability. Collective doses are presented in Table V-20 for the end impact, 193 kph impact speed accident, as an example.

Table V-20. Collective conditional inhalation and external dose risks for the 16 routes analyzed.

	Collective Inhalation Dose Risk (person –Sv)				Collective External Dose Risk (person –Sv)			
	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE YANKEE								
RURAL	2.81E-14	1.23E-14	1.80E-14	8.49E-	2.37E-	1.03E-	1.51E-17	7.14E-18
SUBURB	5.54E-13	3.53E-13	2.98E-13	1.76E-	4.66E-	2.97E-	2.51E-16	1.48E-16
URBAN	9.66E-12	5.93E-12	5.08E-12	2.57E-	8.10E-	4.98E-	4.26E-15	2.16E-15
KEWAUNEE								
RURAL	1.11E-14	2.62E-15	2.79E-15	2.79E-	9.37E-	2.20E-	2.35E-18	2.35E-18
SUBURB	2.37E-13	1.19E-13	1.11E-13	1.01E-	1.99E-	1.00E-	9.34E-17	8.53E-17
URBAN	4.18E-12	1.99E-12	1.95E-12	1.37E-	3.50E-	1.67E-	1.64E-15	1.15E-15
INDIAN POINT								
RURAL	3.06E-13	9.96E-15	1.05E-14	4.21E-	2.57E-	8.38E-	8.82E-18	3.54E-18
SUBURB	9.52E-12	3.57E-13	3.61E-13	1.33E-	8.01E-	3.00E-	3.04E-16	1.12E-16
URBAN	1.64E-10	6.37E-12	6.55E-12	2.06E-	1.38E-	5.34E-	5.49E-15	1.73E-15
IDAHO NATIONAL LAB								
RURAL	9.03E-06	3.60E-07	4.01E-10	1.20E-	9.03E-	3.60E-	4.01E-10	1.20E-08
SUBURB	1.23E-08	2.37E-10	3.43E-13	2.21E-	1.23E-	2.37E-	3.43E-13	2.21E-11
URBAN	4.43E-07	2.06E-08	2.38E-11	7.52E-	4.43E-	2.06E-	2.38E-11	7.52E-10

Inhalation doses include doses from direct inhalation and from material resuspended in air. External doses include cloudshine and groundshine. The NRC cites the total effective dose equivalent (TEDE) which includes both inhalation (internal) doses and external doses. The complete collective dose risk is the product of the collective dose risk as shown in Table V-21 and the accident frequency along the route. Average accident frequencies for each route are in Table V-8.

Table V-21 shows the total dose risk for each route.

Table V-21. Total collective dose risks (person-Sv) for each route

	ORNL	DEAF SMITH	HANFORD	SKULL VALLEY
MAINE	2.47E-08	5.97E-10	1.06E-10	9.81E-11
KEWAUNEE	8.85E-07	4.12E-08	8.80E-11	1.53E-09
INDIAN POINT	3.40E-09	1.31E-10	1.35E-10	4.29E-11
INL	2.09E-11	3.36E-11	9.08E-12	6.07E-11

V.6. Summary

The more important technical observations for the analysis of accidents are:

- Event trees based on current accident statistics show that the probability of a severe accident for either truck or rail is small (chance is 1 in 10,000,000 or less).

Comment [JRC35]: We need to characterize "small" – this is a placeholder.

- The probability of a fire that would damage a cask on a railcar enough to cause loss of gamma shielding or release of radioactive material is negligible.
- The analyses in Appendices III and IV demonstrate that the only cask that would suffer a loss of lead shielding or release of radioactive material is the Rail-Pb cask. This is the only cask whose behavior in loss of shielding or release accidents is analyzed.
- The fraction of accidents that do not lead to either a release of radioactive material or a loss of lead gamma shielding is 0.999991.
- Loss of more than two percent of the lead shield results in a dose that exceeds the limits of 10 CFR 71.51 for a person within four meters of the cask.
- If the fuel rods are not breached in an accident, there would be no net flow of gas out of the cask, and nothing would be released.
- Weather conditions that result in poor dispersion, very stable Pasquill Stability Class F and wind speed at 0.5 m/sec, resulted in doses very little different from those for neutral, more average weather conditions, and are therefore not reported.

Comment [JRC36]: ...there would be no releases from canistered fuel; the

Comment [JRC37]: Was this distance analyzed? Is this a summary observation?

Comment [JRC38]: If you don't breach the cask, doesn't matter whether fuel rods are breached or not.

Comment [JRC39]: Seems a minor point, not final conclusion for summary?